

As the start of the rainy season approaches, it is appropriate that this issue cover analysis of past and future climate conditions, focusing on the status of the science in these areas. In a perfect world, climatologists and meteorologists would be able to furnish accurate, detailed predictions of long-term temperature and rainfall patterns, allowing water managers to plan accordingly. Unfortunately such information is not available, and water managers are forced to use whatever tools may be available to assist in making decisions with less than perfect information.

Water project operation and planning have traditionally been based on analysis of the historical period of measured hydrologic data, which provides no more than about 100 years of usable information. Paleoclimate information, typically from tree-ring analyses, can be used to reconstruct streamflows prior to the historical record, important background for evaluation of water projects under sustained severe drought conditions. Such information is particularly important in major river basins like the Colorado, where there is a high level of dependence on a fully allocated resource. However, knowledge of past climate variability alone may not be sufficient, as human-induced climate change may affect future conditions of interest to water managers. In particular, data collected from Sierra Nevada watersheds have been cited as the canary in the coal mine with respect to conditions that water managers may face in the future.

RECORDED IN THE RINGS

The application of tree-ring data to sustainable water management in California and the West

by Jeff Lukas¹ and Connie Woodhouse^{1,2}

Water managers in the Western U.S. have usually relied on the gaged records of streamflow to anticipate likely future variations in water supply, but these records are simply too short (20 to 100 years) to capture the full range of flow variability. To provide a longer window on past variability, water managers at California Department of Water Resources (CDWR) and elsewhere in the West have been turning to tree-ring scientists, or dendrochronologists. The ring-widths of moisture-sensitive trees are used to reconstruct streamflow 300 years or more into the past. These multi-century reconstructions are likely to show more of the full range of variability, including the extreme droughts of most concern to water management.

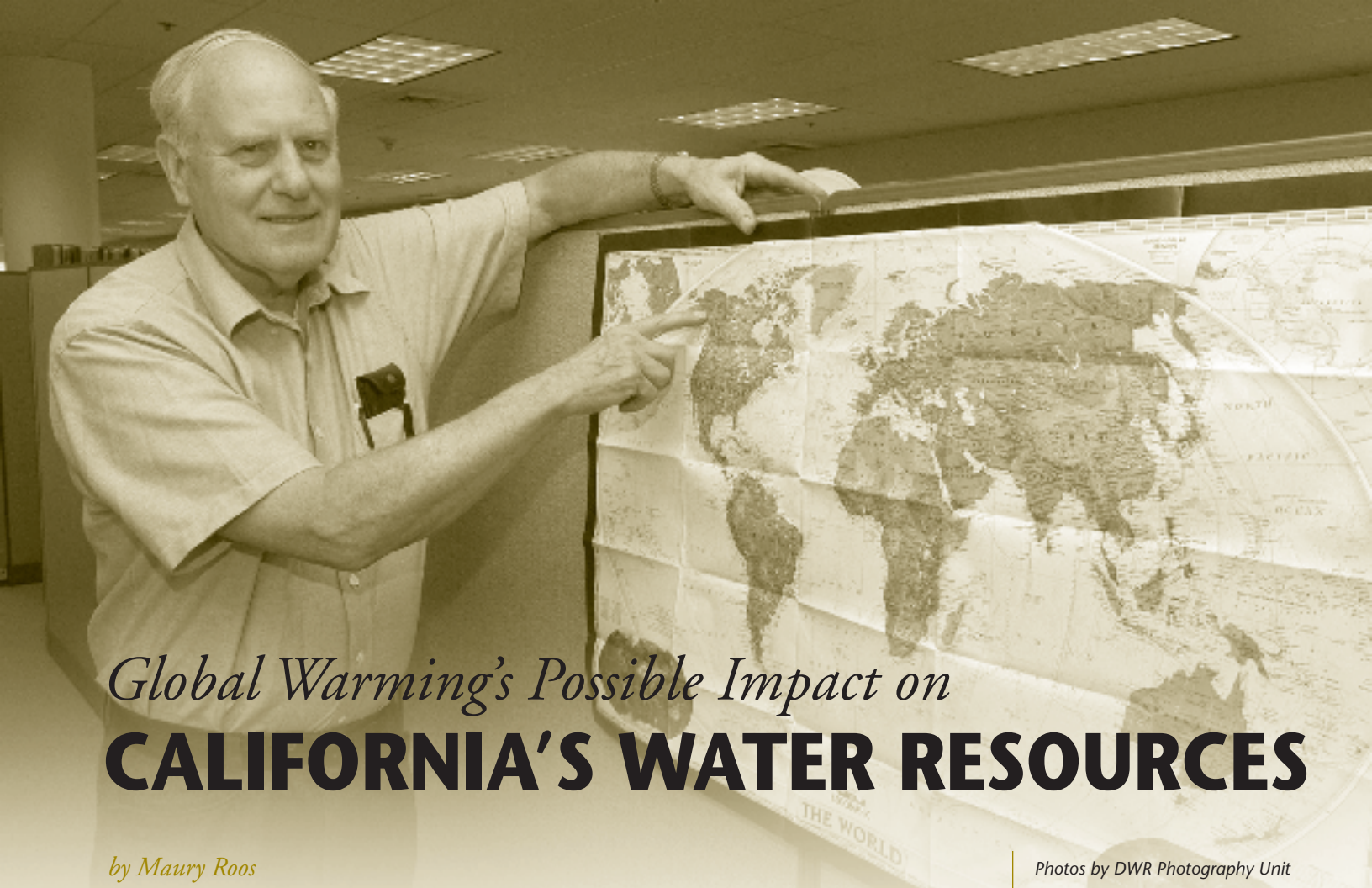
Background

The first studies to examine the relationship between tree growth and streamflow in the Western U.S. were carried out in the 1930s and 1940s. By the mid-1970s, researchers at the University of Arizona had developed a 440-year reconstruction of annual streamflow for the Colorado River at Lee's Ferry. This highly influential study showed that there had been droughts on the upper Colorado—most notably in the late 1500s—that were both longer and more intense than those of the 1930s and 1950s. It also showed that the first two decades of the 20th century—the period on which the Colorado River Compact was based—was probably the wettest 20-year period in over four centuries.

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Global Warming's Possible Impact on **CALIFORNIA'S WATER RESOURCES**

by Maury Roos

Photos by DWR Photography Unit

In recent years, evidence has continued to accumulate that global climate change will have significant effects on California's water resources. Global warming has the potential of affecting a wide variety of water resources elements. These include water supply, hydroelectric power, sea level rise, more intense precipitation and flood events, water use and water temperature changes. Causes can be natural or of human origin. A major cause of the expected change is increasing amounts of greenhouse gases, such as carbon dioxide, in the atmosphere as a result of human activities. Other significant greenhouse gases are methane, nitrous oxide, halocarbons (like freon and its replacements) and, of course, water vapor itself.

The earth already has a strong greenhouse effect, about two-thirds due to water vapor and 25 percent due to carbon dioxide. Without this, average world temperatures would be around 0 degrees Fahrenheit instead of the 60 degrees we enjoy. The concern is that increases in greenhouse gases will change the radiation balance, leading to a rise in global temperatures this century. A rise of about 1°F has been

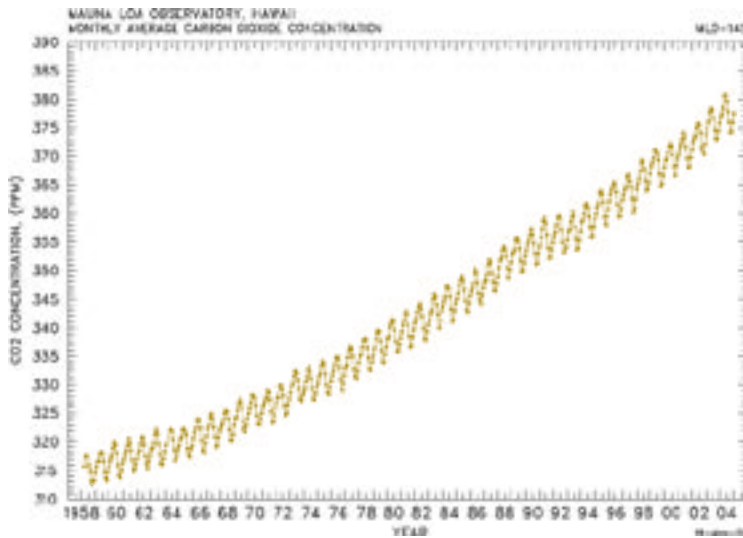
Above: Maury Roos explains Global warming's potential impacts on other parts of the nation.

estimated for the 20th century, partly of natural causes, as a rebound from the "Little Ice Age" of preceding centuries. In 2000, an international group of scientists projected a global temperature increase by year 2100 of about 3°C (5°F) with a range from 1.4° to 5.8°C.

Carbon dioxide in the atmosphere has been increasing slowly. The measurements atop Mauna Loa, Hawaii, were started by world renowned scientist Dr. Charles David Keeling of Scripps in 1958 and are the longest continuous record of atmospheric CO₂ concentrations in the world. (Dr. Keeling died in June 2005 at the age of 77; his monitoring work is being continued by Dr. Timothy Whorf.) The annual cycle is caused by northern hemisphere vegetation uptake during the growing season. The average rate of increase the past several decades has been 1.6 ppm per year. The source is mostly from burning fossil fuel. The USA's estimated share of world CO₂ emissions in year 2000 was 23 percent. China was next at 11 percent.

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Atmospheric Carbon Dioxide Concentration as Measured at Mauna Loa, Hawaii



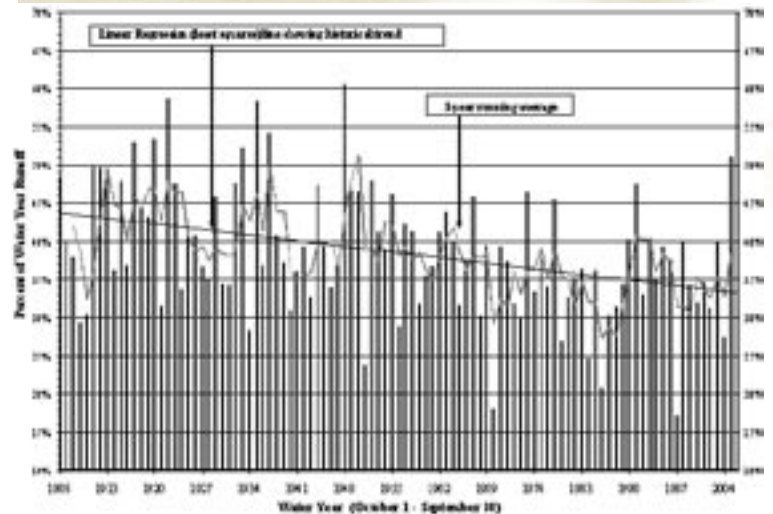
Source C. D. Keeling and T. P. Whorf, Scripps Institution of Oceanography, via C. D. I. A. C., Oak Ridge Nat. Lab.

Significant changes in climate during this century are projected due to global warming. These changes are expected to affect many of our water resources systems. Many of the more important changes would arise from temperature increases, which would raise mountain snow elevations (by about 500 feet per degree Celsius) and change mountain watershed runoff patterns—more in winter, less in spring and early summer snowmelt, thereby affecting reservoir operations. Other consequences include sea level rise, which could adversely affect the Sacramento-San Joaquin Delta, a major source of water supply for California, possibly more extreme precipitation and flood events, changes in water use for crops and wildlands, and water temperature problems for anadromous fish.

Some of these changes appear to be happening. The fraction of water year runoff coming during the April through July traditional snowmelt season, although highly variable from year to year, seems to have been decreasing during the past 50 years. This effect is more noticeable in the lower elevation northern Sierra than the higher elevation southern Sierra. The next chart shows the percentages for the Sacramento River system, the four major rivers of the Sacramento River region (Sacramento River near Red Bluff, and Feather, Yuba and

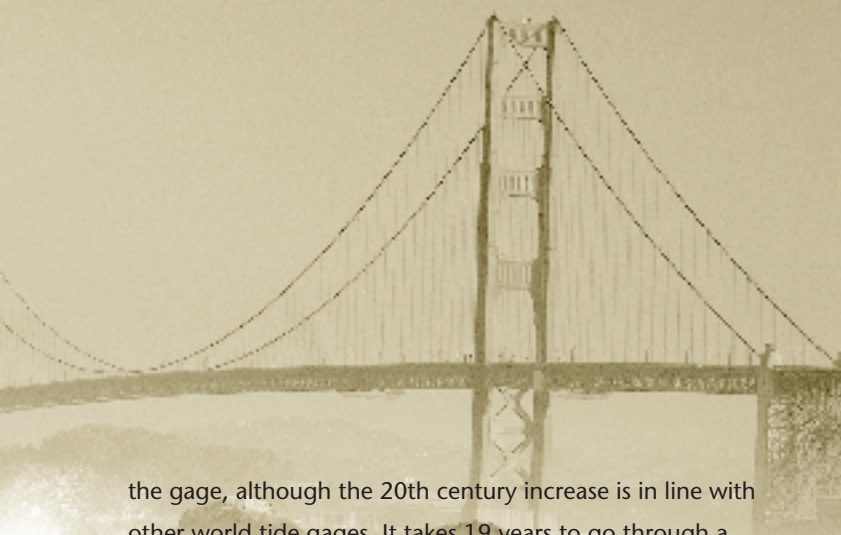
American Rivers). This current water year, 2005, has bucked the trend with a 51 percent fraction based on current late season forecasts. This shift, if it continues, will make it more difficult to fill our major foothill reservoirs because of less snowmelt in the late spring. Lower reservoir levels could reduce dry season water supply and, because of lower head, reduce hydroelectric power production.

Sacramento River April-July Runoff in Percent of Water Year Runoff



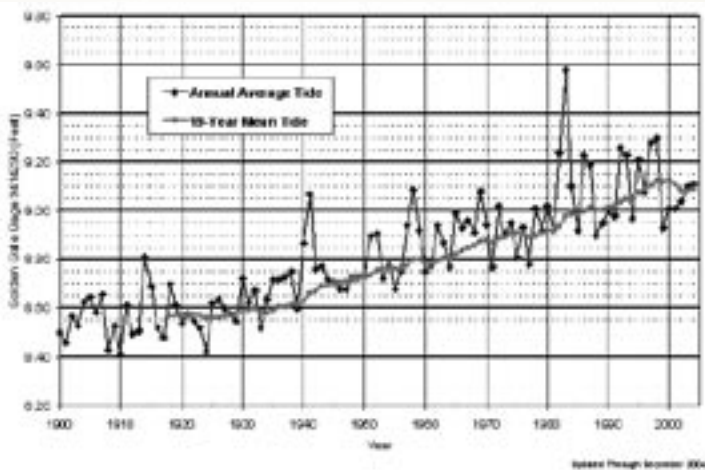
A second major impact is sea level rise, which would affect many low areas along the coast. But the major water systems impact would be in the Delta. There the problem would be two-fold: (1) problems with the levees protecting the low lying land, much already below sea level; and (2) increased salinity intrusion from the ocean, which would degrade fresh water transfer supplies pumped at the southern edge of the Delta or require more fresh water releases to repel ocean salinity. The international science panel (Intergovernmental Panel on Climate Change), in their year 2000 report projected sea level rise by 2100 to range from about 0.3 to 3 feet, with a median of about 1.6 feet. During the past 75 years or so, the measured rate of rise at the Golden Gate tide gage has been about 0.7 feet per century. Much of this is believed to be from melting temperate zone glaciers, particularly in southern Alaska.

The chart depicts the average annual sea level stages at the Golden Gate, which is measured by the National Ocean Service. It is possible that tectonic earth movements may be influencing



the gage, although the 20th century increase is in line with other world tide gages. It takes 19 years to go through a complete lunar cycle, which is the reason for the 19-year average line. The last decade shows a slowing of the rate of rise; this may be temporary.

Golden Gate Annual Average and 19-year Mean Tide Levels



More extreme precipitation events generally go along with increasing temperatures. This is the kind of information in the form of statistics on rainfall depth, duration, and frequency that go into storm drainage design. The problem may be compounded in the high elevation river watersheds of the Sierra Nevada. Here, with higher storm snow lines, a greater fraction of the watershed could be producing direct rain runoff, with larger flood volume.

There are likely to be changes in water use as well as water supply. Water consumption changes are likely to be small, but because so much land is involved, amounts could be very significant. Generally, a slightly warmer climate with less frost and a higher atmospheric concentration of carbon dioxide is regarded as beneficial to many food crops. As a rule, plant evapotranspiration increases with temperature. Higher carbon



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Maury worked 43 years for DWR as a water engineer. As a Retired Annuitant, he provides advice on flood forecasting, hydrology, water supply and snowmelt forecasting and staff meteorology. Related topics include floods and droughts, global warming, and weather modification, and participation in elements of the California Water Plan Update (Bulletin 160). For years he has been attempting to track climate change issues, as well, especially as they relate to water supply in California.

He received a BS degree in Civil Engineering from San Jose State University in 1957.

In September of 2005, Maury went to the International Commission on Irrigation and Drainage Congress in Beijing, China. He presented a workshop paper on Northern California flood management and served on two working group meetings.

dioxide levels, however, reduce water consumption (at least in laboratory tests), and seem to increase yield on some crops. Some weeds, including water weeds, may thrive better too. Most likely, the higher water consumption due to warmer temperatures will only be partly offset by the carbon dioxide-based reductions. Thus, the net effect could be slightly higher agricultural and landscape water requirements. For some annual crops, it may be possible to change the planting season a few weeks which may result in no net change for that crop.

Warmer water temperatures could be of considerable concern in managing salmon and steelhead fisheries. Warmer air temperatures will make it more difficult to maintain rivers cold

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enough for cold water fish, including anadromous fish. With reduced snowmelt, existing cold water pools behind major foothill dams are likely to shrink. As a result, river water temperatures could warm beyond the point tolerable for salmon and steelhead that currently stay in these rivers during the summer and early fall. Some reservoirs have multi-level outlets to help control water temperatures. These kinds of outlets may have to be installed on other structures.

These are five of the potential major effects of global warming on water resources in California. There are undoubtedly others, such as a longer fire season in the mountains. Impacts on the Colorado River are of concern to California as well. That basin is not so vulnerable to changing runoff patterns with less snowmelt because of ample storage on the main stem. However, its total runoff is quite sensitive to small changes in average precipitation. One would expect warmer temperatures to dry out the water-producing region of its vast watershed somewhat sooner than today.

The Department of Water Resources has given significant space and discussion of climate change in the most recent Bulletin 160 "California Water Plan Update." During the next few years, Department planning staff will be trying to develop a better quantitative sense on what climate change will do to water resources systems operation and what measures may be useful in providing for all California water needs in a world with a warmer climate.

Interest in climate change and greenhouse gas emission reductions at the State level led Governor Schwarzenegger to issue an executive order in June 2005, setting goals for reducing California emissions by 2010 to year 2000 levels and by 2020 to 1990 levels. He also asked for a report by January 2006 on impacts to California of global warming, including impacts to water supply, public health, agriculture, the coastline, and forestry and reporting on mitigation and adaptation plans to combat these impacts. Several DWR people, primarily from the planning, modeling and hydrology groups, will be involved in helping with the report, which is assigned to the Secretary of the California Environmental Protection Agency.

Recorded in the Rings continued from page 4

During the 1980s and 1990s, many new moisture-sensitive tree-ring chronologies were collected from Pacific Coast states, creating new opportunities for reconstructing streamflow in this region. In the mid-1980s, **Christopher Earle** and **Harold Fritts**, in work funded by the CDWR, developed 420-year reconstructions of four gage records in the Sacramento River Basin. In the late 1990s, in another CDWR-funded study, **David Meko** of the University of Arizona and others extended Earle's work, producing a reconstruction of Sacramento River flow back to AD 869. They found, as Earle did, that the six-year 1930s drought was severe even in the context of the tree-ring record. But there were many reconstructed droughts both shorter and longer than six years, particularly before 1400, that appear worse than those since 1900. Work by **Hugo Loaigiga**, **Joel Michaelsen** and others at the University of California that assessed the statistical characteristics of drought based on tree-ring reconstructions of streamflow in California and the Colorado River basin was also done during this period.

Tree-ring research in the Colorado River basin has also progressed. **Connie Woodhouse** of NOAA and the University of Colorado, along with David Meko, and **Stephen Gray** of the USGS, have just used a dense network of new tree-ring records in Colorado, Wyoming, and Utah to develop a new reconstruction of the Colorado River at Lee's Ferry.

Developing the reconstructions

In most parts of the West, annual tree growth closely reflects the amount of soil moisture at the onset of the growing season, which is controlled mainly by winter-spring precipitation. Trees that provide the best information about streamflow variability—those particularly sensitive to variations in moisture—include species such as ponderosa pine, western juniper, and blue oak, growing in open stands on dry sites where soil moisture storage is minimal.

A tree-ring reconstruction of streamflow is developed from multiple tree-ring records, or chronologies. A tree-ring chronology is a time-



The patterns of wide and narrow growth rings of a pinyon pine (upper core) and Douglas-fir (lower core) record fluctuations in moisture. [Image by Jeff Lukas]

series of annual values derived from the ring-width measurements of 10 or more trees of the same species at a single site. To create a tree-ring chronology, cores from the sampled trees at each site are crossdated (patterns of narrow and wide rings are matched from tree to tree) to account for missing or false rings, so that every annual ring is absolutely dated to the correct year. Then all rings are measured to the nearest 0.001 mm. After age-related trends in growth are statistically removed, the ring-width values from all sampled trees for each year are averaged to create a time series of annual ring-width indices: the chronology.

Once a gaged natural flow record of interest is selected for reconstruction, chronologies from the region around the gage are calibrated with the gage record to form a reconstruction model. The reconstruction model is then validated by testing it on a portion of the gage data that was withheld from the calibration process. Since there is always some portion of the variability in the gaged record that the trees do not explain, various statistics can then be used to describe the uncertainty inherent in the reconstruction.

Other proxies of past climate confirm and complement the information contained in the tree-ring reconstructions. Oxygen isotope ratios in lake bottom sediments (e.g., in Mono Lake) have been used to reconstruct the water balance in the lake, and thus changes in the regional climate. Dead trees rooted at the bottom of Lake Tahoe and other Sierran lakes have been radiocarbon-dated, indicating when the lake was at a low stand caused by sustained drought. But only tree rings have the combination of annual resolution, dating to the exact calendar year, and high sensitivity to moisture that allows for direct reconstruction of annual streamflows.

Applying the reconstructions to water management

Reconstructed streamflows have been used by water managers in a number of ways to help guide planning. They can be considered qualitatively to provide a broader perspective on the flow variability seen in the gaged record. They can be used directly as inputs into water supply models to test the ability of their systems to meet demand under the broader range of flow conditions represented by the reconstructions. They can also be used to generate probabilities for different drought scenarios, and to construct a “design drought” used as a worst-case scenario in planning.



Climatologist **Mark Losleben** cores a ponderosa pine growing out of a granite outcrop near Lake George, Colorado. The core from this tree contains a multi-century record of moisture variability that can be used to reconstruct streamflow. [Photo by Connie Woodhouse]

Ongoing projects

Several collaborative projects are either ongoing or just starting up. David Meko and **Katherine Hirschboeck** of the University of Arizona have been working with water managers with the Salt River Project (Arizona), using tree-ring reconstructions of streamflow to assess how often the Colorado and Salt-Verde basins have been in simultaneous drought. The Salt River Project relies on water from both basins.

Meko is also working on a project led by **David Stahle** of the University of Arkansas, and funded by CALFED, to use blue oaks to reconstruct streamflow and precipitation in the Central Valley of California. Meko and Woodhouse are also collecting remnant material (stumps and logs) at sites in the Colorado Basin to extend the Lee's Ferry reconstruction further back into the past. Researchers from the University of Colorado, University of Arizona, Scripps/USGS, and NOAA are planning follow-up activities stemming from a workshop for Colorado River water managers and dendrochronologists that was held in Tucson in May 2005.

Where to Get Streamflow Reconstruction Data

<http://www.ncdc.noaa.gov/paleo/recons.html#hydro>

<http://www.ncdc.noaa.gov/paleo/treering.html>

<http://www.ncdc.noaa.gov/paleo/streamflow/>